

that a temporary power boost can be provided to combat fades on selected links while requiring only a modest increase in satellite solar array power. The array power not needed during clear-sky operation is used to charge batteries, which supply the energy needed to transmit the added power during fades.

Through power control, the maximum amount of rain attenuation that can be compensated is equal to the difference between the maximum output of the Earth station or satellite power amplifier and the output required under clear-sky conditions. The effect of power control on availability, assuming that control is perfect, is the same as having this power margin at all times. A perfect power control system varies the power exactly in proportion to the rain attenuation. Errors in the power control result in added outages, effectively decreasing this margin. Maseng and Baaken (1981) have studied this effective margin reduction due to power control delay.

A drawback of power control is a potential increase in intersystem interference. A power boost intended to overcome rain attenuation along the direct Earth-space path will produce an increase in power on interfering paths as well. If the same rain fade does not exist on these paths, the interference power received by interferees, such as other terrestrial stations, will increase. Due to the inhomogeneity of heavy rain, attenuation on interfering paths at large angles from the direct earth-space path will often be much less than the attenuation on that path. Terrestrial system interference caused by the earth station, although tolerable under clear-sky conditions, may therefore become intolerable in the presence of rain when uplink power control is used. Downlink power control will likewise increase the potential for interference with earth stations using adjacent satellites. A downlink power boost for the benefit of a receiving station experiencing a rain fade will be seen as an increase in interference by vulnerable stations that are not experiencing fades.

7.4.3.1.1 Uplink Power Control

A frequency-division multiple-access (FDMA) satellite communication system trying to operate with large spatial and time variations in rain fades will experience significant nonlinear distortion when fades are mitigated by the use of large power margins alone. Nonlinear distortion, which occurs when the satellite transmitter is operated near saturation, includes AM-to-PM conversion and generation of intermodulation products.

By continually adjusting the uplink power from each ground station in accordance with uplink fade conditions, variations in the operating point of the satellite TWTA can be minimized, thereby minimizing nonlinear distortion. However, this does not completely solve the problem because downlink rain fades must also be considered. Lyons (1976) showed that if the uplink power control algorithm accounts not only for uplink fades but also for downlink fades, good performance can be achieved in the presence of fading on both links by using uplink power control alone. Although individual signal levels at the satellite receiver will vary widely in this situation, the TWTA operating point will still remain relatively fixed so long as there is a sufficiently large number of users, all having controlled access to the satellite. So if deep fades occur on only a few of the uplink and downlink paths, variations in the received downlink signal levels will be relatively small, thus requiring smaller fade margins.

However, uplink power control of such systems requires that each station accessing the satellite possess knowledge not only of its uplink fade characteristics, but also of the downlink fade characteristics for all stations to which it is transmitting. Power control of all transmitting stations can be achieved from a single location at the cost of control delays, which result in relatively slow fade mitigation. If instead, we have distributed control in the sense that each station controls its own transmitted power, delays are minimized. However, performance may suffer because the total received uplink power at the satellite can no longer be

maintained approximately constant under widely fluctuating propagation conditions. Furthermore, with distributed control, fade information must be exchanged continually among all participating stations to make the system work.

These arguments indicate that if the uplink power control algorithm does not take into account the downlink fade characteristics, then power control can likely be applied only to single-service, single-user links. For such links, there are two types of uplink power control that can be used (Ippolito-1986). The first is a closed-loop system that adjusts uplink power in accordance with the satellite received signal level returned to the transmitting station via telemetry. The second is an open-loop system that adjusts uplink power in accordance with either the downlink signal (or beacon) level, or the attenuation calculated from ground-based radiometer or radar measurements. Figures 7.4-15 and 7.4-16 illustrate closed-loop and open-loop uplink power control for single-carrier links.

7.4.3.1.2 Downlink Power Control

More and more satellite communication systems are going to on-board signal processing, not only to improve bit error rate performance (in the case of digital modulation), but also to improve terminal interconnectivity and to make downlink performance independent of the uplink. On-board processing simplifies power control for rain fade mitigation (especially in FDMA systems) because the uplink power control algorithm no longer needs to take into account downlink fade conditions. Therefore, uplink and downlink power control can be done independently, which alleviates many problems associated with the use of FDMA during rain fades. This assumes that on-board processing includes demodulation to baseband, followed by remodulation onto a downlink carrier. The following discussion assumes that downlink power control can be accomplished essentially independent of the uplink regardless of whether or not on-board processing is being used.

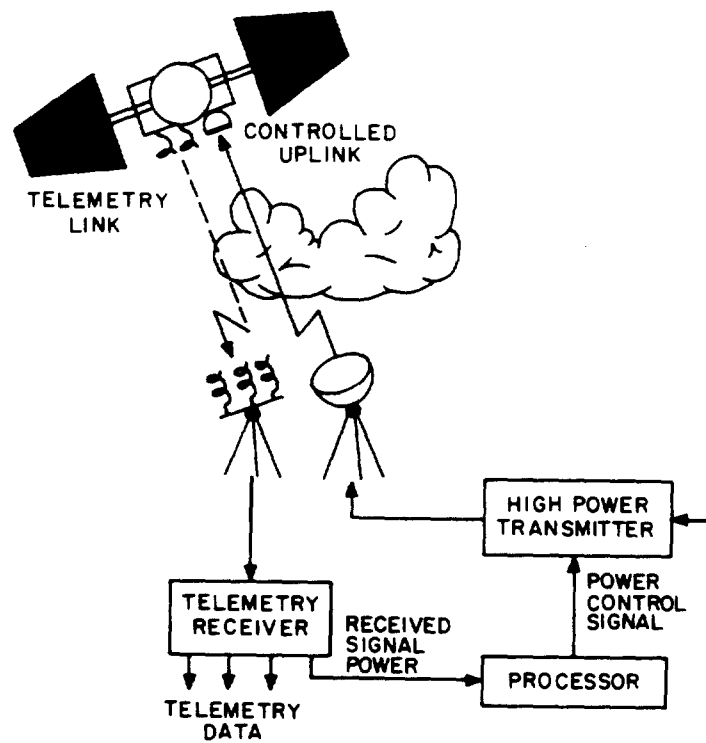


Figure 7.4-15. Closed loop uplink power control

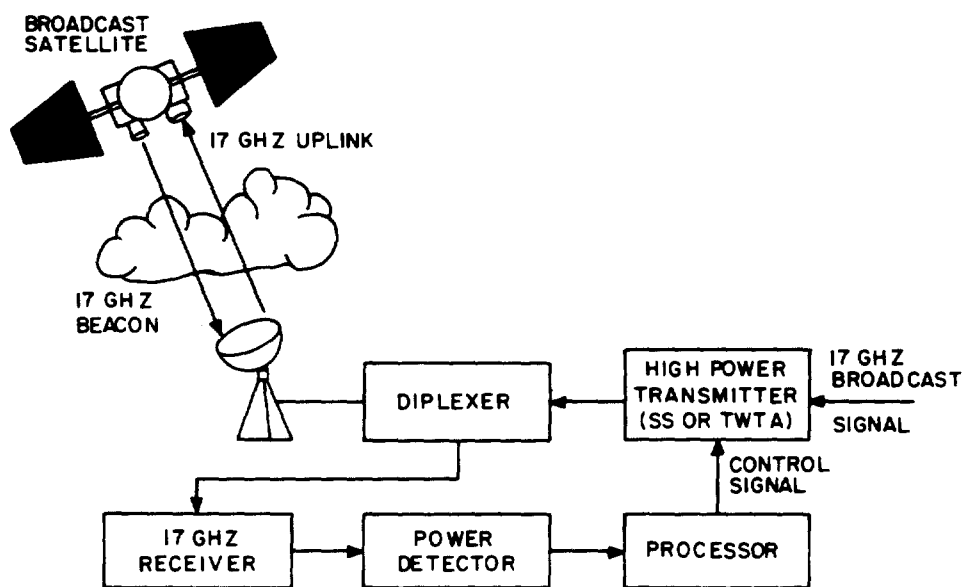


Figure 7.4-16. Open loop uplink power control

The satellite transmitter usually has only one or two switchable output power levels, so downlink power control for rain fade mitigation is less flexible than uplink power control. One example is ACTS (Holmes and Beck-1984), which operates at 30/20 MHz and has a transmitter output power of either 8 or 40 watts. The high-power mode therefore provides 7 dB additional margin against rain fades. Because the entire antenna footprint receives the added power in the high-power mode, those stations not experiencing rain attenuation will receive more power than they require. Downlink power control is therefore not efficient in directing the added power to the stations needing it.

This problem with downlink power control is somewhat alleviated by the use of switchable spot beams on the satellite. The reason for this is that the antenna footprints are relatively small, thereby allowing added downlink power to be directed only to those terminals that require it. In fact, switching to spot beams is, in itself, an effective technique for mitigating rain fades, even when satellite transmitter power is not controlled. The use of downlink power control together with switchable antenna beams might better be called EIRP control rather than power control.

7.4.3.2 Adaptive Forward Error Correction. In Time Division Multiple Access (TDMA) systems, each earth station is periodically assigned a time interval during which it alone may access the entire satellite bandwidth. The time between accesses by a given station is called the TDMA frame period, and each station is assigned a fixed fraction of the frame. This fraction is proportional to the traffic the station is carrying, or to its average bit rate. By leaving a portion of the frame period unassigned, those stations experiencing rain fades can be temporarily assigned a larger fraction of the frame for fade mitigation. One way to exploit this additional time resource is to apply forward error correction (FEC). The same number of information bits is transmitted each frame period as before. However FEC reduces the required received signal level, thereby at least partially offsetting the loss in received power

experienced during rain fades. Alternatively, the additional allotted time allows a reduction in data rate during rain fades. Data rate control will be discussed further in paragraph 7.4.3.4.

This scheme is adaptive in the sense that FEC is applied only when the rain attenuation has exceeded a selected threshold. When FEC is used, the symbol timing hardware still operates at the same fixed rate. In principle, FEC can be implemented in software, which may be advantageous in some systems.

There is a limit to the mitigation that coding can provide (Bronstein-1982). This is because a minimum symbol energy must be maintained to ensure proper recovery of symbol timing in the receiver. Therefore, because the symbol rate is fixed, a minimum received signal power level must be maintained. The fade margin achieved with FEC must be traded off against the reduction in total system capacity that occurs. As propagation conditions worsen, the fraction of the frame duration needed for fade mitigation must increase, thereby reducing the fraction available for use during clear weather.

FEC can be used to mitigate either uplink or downlink fades. A station affected by uplink fades would encode its entire burst - lengthening its burst period by its allotted reserve time. Each station receiving that station's burst must decode the data in that burst. In contrast, a receiving station affected by downlink fading will receive all its data in coded form. Transmitting stations must encode that portion of the data that is transmitted to the affected station. It is apparent that a central control station must dynamically assign the extra time to the stations that require it. Furthermore, all stations in the network must know which stations require coding.

A satellite using on-board signal processing essentially decouples the downlink from the uplink, which allows the reserve time to be used more efficiently. Only those transmitting stations experiencing uplink fades then need to encode their data. The

satellite would not only demodulate the uplink signal, but would also decode those uplinks affected by fading. The satellite would then encode for downlink transmission only those signals affected by downlink fades. The reserve time used by faded uplinks is, in effect, freed up to be used by faded downlinks.

Acampora (1979, 1981) has studied the performance of a system using FEC coding to mitigate downlink fades. The hypothetical TDMA system studied operated in the 12/14 GHz bands, using a bent-pipe transponder. The traffic model used assigned traffic between the 100 most populous U.S. cities in proportion to their population ranking. The Earth stations were given a built-in fade margin, and the reduction in this margin made possible by time resource sharing was found, using a convolutional FEC code that gave a 10 dB power saving. A typical result of this analysis showed that reserving six percent of the frame period as a shared resource provided an outage of 30 minutes per year (.0057% of the time) with 9 dB less rain margin than would otherwise be needed.

Gains of up to 8 dB have been reported (Mazur, et. al.-1983) for 14/11 GHz TDMA networks with 32 ground terminals. Five of the 8 dB comes from the coding gain provided by a rate 1/2 code. The other 3 dB comes from a QPSK/PBSK switch capability.

7.4.3.3 Frequency Diversity. A straightforward method of improving the reliability of a millimeter-wave satellite system is to provide the capability for Earth stations to switch to a lower frequency band (say C-band) when rain fades occur at the normal operating band. This would require a satellite with a dual-band payload and a dual-frequency Earth station capability, but the improvement in overall system reliability may be worth the added cost. The bandwidth required in the lower, high-reliability, frequency band need be only a fraction of the total bandwidth used, since it needs to accommodate only the traffic of those stations undergoing rain fades. The probability of rain outage on a particular link with such a frequency diversity system is equal to the sum of the probabilities of two mutually exclusive events: (1) that the

reserve band is fully occupied by other links when a rain fade occurs, and (2) that a link is assigned to the reserve band, but the rain rate is so great that the reserve band suffers an outage while the link is using it. If 4/6 GHz is used for the reserve band, the probability of the second event can be considered nil. If the reserve band is wide enough for N links, the probability of the first event is the probability of N+1 simultaneous fades. The bandwidth required in the reserve band is therefore established by the simultaneous fade probability over all the Earth stations in the system. The dependence of system performance on simultaneous fade probability is common to all resource-sharing schemes. Because of this, it will be discussed separately later (paragraph 7.4.4).

7.4.3.4 Data Rate Control. If the satellite receiver monitors the uplink received signal level and feeds this information back to the transmitter, then various properties of the transmitted signal can be varied to mitigate uplink rain fades. Transmitter power control (paragraph 7.4.3.1) provides an example. However, we can vary the data rate rather than the transmitted power to accomplish the same results. This is because in digital data transmission the measure of system performance is the bit error rate, which ideally depends only on the received bit energy-to-noise density ratio. The bit energy in turn is equal to the received signal power divided by the data rate. So in principle, lowering the data rate by a factor of two, for example, has the same effect on error rate performance as raising the transmitted power 3dB.

It has been shown (Cavers-1972) that data rate control can completely eliminate the effect of fading if the feedback from the receiver is assumed to be ideal (no control delay). Even when control delay is included, however, data rate control can often be more effective than diversity reception, at a cost of bandwidth expansion to accommodate transmission of control information.

As we have seen in paragraph 7.4.3.2, a possible fade mitigation technique for TDMA communication is to leave a portion of the frame period unassigned - making it temporarily available to those

stations experiencing rain fades. Data rate control of such systems involves transmitting or receiving the same number of information bits each frame during the fade, but reducing the data rate in order to fully occupy the additional allotted time. As discussed above, this increases the transmitted energy per bit, which offsets the loss in received power during the fade.

For data rate control to work, the ground stations must at least have the synchronization hardware required to switch from the normal symbol rate to a lower rate. However, to achieve performance approaching that obtained when there are no fades, the use of several selectable data rates is required, with little delay in the control loop.

As with adaptive FEC coding, data rate reduction can be used to mitigate both uplink and downlink fades. Again, on-board signal processing essentially makes uplink data rate control independent of downlink control, thereby making efficient use of the reserve time and simplifying the control procedure. However, the satellite receiver must be capable of synchronizing to several data rates, which complicates the on-board processing hardware.

7.4.4 Simultaneous Fade Probabilities

When a resource-sharing scheme is used to provide additional fade margin, the amount of the resource (time or frequency) that must be set aside to provide the required margin is highly dependent on the probability of simultaneous fades on two or more links. If sufficient resources are reserved to back up two links, for example, then the outage probability is the probability that the fade depth exceeds the added margin provided, or that three or more links are suffering fades at the same time.

The probability of simultaneous fades is also of interest in connection with site diversity systems (paragraph 7.4.2.1). In that case, the sites are generally assumed to be close enough to each other to be affected by the same storm system. In the case of

resource-sharing systems, we are concerned with fades simultaneously occurring on links to Earth stations separated by much larger distances as well. A naive approach would be to assume that the rain attenuation at a given Earth station is statistically independent of that at another station substantially removed from the first. Closer examination reveals, however, that this is not the case.

Acampora (1981), in the analysis cited earlier, observed that the deep rain fades that are of concern are normally caused by thunderstorm activity, and that there is a definite correlation in thunderstorm activity at widely separated locations. In particular, thunderstorm activity is typically restricted to the four-month period from June through September, and to the quarter of the day lasting from 1:00 PM to 7:00 PM local time. Because of this, the occurrence of a deep fade at one site makes the probability of a deep fade at the same time at a second site much higher than the yearly average. The observation of the fade at the first site makes it highly probable that we are in the June-September, 1:00 PM - 7:00 PM thunderstorm period, therefore the chances of a thunderstorm at the second site are higher than average by a factor of at least $(12/4)(24/6)$, or 12, using the broad ranges of time given. In addition to this yearly-to-thunderstorm-period factor, α , a second factor β , accounts for the additional correlation of deep fades between sites that are spaced closely enough that they are affected by the same storm systems. This factor was considered by Acampora to range from 1, which implies independence of fades during the thunderstorm period, to a maximum value of 6. The factors α and β are applied as follows: The yearly average joint probability of the attenuation (A_1 and A_2) two sites exceeding their respective thresholds (T_1 and T_2) is given by

$$P(A_1 > T_1, A_2 > T_2) = \alpha \beta P(A_1 > T_1) P(A_2 > T_2)$$

where the last two quantities are the individual yearly exceedance probabilities for the two sites. For $T_1 = T_2$, the factor $\alpha\beta$ is seen to be the diversity improvement defined in Section 7.4.1.

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SUBJECT INDEX

-A-

- Adaptive forward error correction, 7-79, 7-117
- Advanced Communications Technology Satellite (ACTS), 7-18, 7-24, 7-78, 7-117
- Amplitude dispersion data, 5-39
- Amplitude fluctuations, 6-76, 6-101, 6-126, 6-129
- Angle diversity (see: Orbit diversity)
- Angle-of-arrival
 - definitions, 6-94
 - fluctuations, 6-103
- Antenna
 - aperture effects, 6-75
 - axial ratio, 4-15
 - gain equation, 7-52
 - non-ideal performance, 4-15
 - wave interaction, 4-8
- ATDRSS, 7-35
- ATS-5 satellite, 5-21
- ATS-6 satellite, 4-40, 5-3, 5-4, 5-22
- Attenuation
 - clear-air, see gaseous
 - cloud, 1-4, 7-63
 - co-polarized (CPA), 4-33
 - differential, 4-29
 - dust, 6-73, 7-63
 - fog, 1-4, 6-71
 - gaseous, 6-7, 7-63
 - rain, 1-6, 3-1
 - sand, 6-73
 - specific rain, 2-7, 2-11, 4-25
- Attenuation, rate of change, 6-56
- Attenuation statistics
 - 11.5 - 11.7 GHz, 5-8
 - 15 - 16 GHz, 5-18
 - 19 - 20 GHz, 5-22
 - 28 - 35 GHz, 5-22
 - analytic estimates, 6-20
 - diurnal distribution, 5-29
 - elevation angle scaling, 5-15, 6-48
 - extension, 6-44
 - extension example, 6-48
 - fade duration distribution, 5-35
 - format, 5-5
 - frequency scaling, 5-25, 6-47
 - histograms, 5-27, 5-31, 5-34
 - joint attenuation - depolarization, 5-36, 7-60

- monthly distribution, 5-28
- prediction
 - from limited rain rate and attenuation statistics, 6-43
 - from rain rate statistics, 6-41
 - using CCIR model, 6-32
 - using Global model, 6-23
- procedures for calculating, 6-20
- worst month, 6-59
- Availability, 7-8, 7-73
- Axial ratio 4-7, 4-16

-B-

Bandwidth coherence

- ionospheric effects, 6-129
- tropospheric effects, 6-126

Beacons (see: Propagation beacons)

Bit error rate, 7-9

BS satellite, 5-3, 5-4

-C-

Canting angle, 4-29, 4-37

CCIR (International Radio Consultative Committee), 5-1, 7-9

- rain attenuation model, 3-2, 3-44, 6-32, 6-37
- sample calculation, 6-35
- rain depolarization model, 4-36

Clear-air attenuation, 6-7, 7-63

Clear-air fluctuations, 6-75

Climatological Data Reports, 2-16

Clouds

- attenuation statistics, 6-67
- measured attenuation, 6-64
- water content, 6-64

Coherence bandwidth

- amplitude variations, 6-126
- experimental results, 6-127
- ionospheric effects, 6-129
- phase variations, 6-129
- tropospheric effects, 6-126

COMSTAR satellite, 4-40, 5-4, 5-22, 5-28, 5-29, 5-36, 5-39

Copolarized attenuation (CPA), 4-33, 5-33

Copolarized wave, 4-2, 4-15

Crosspolarization, 1-6

- discrimination (XPD), 4-2, 4-13, 4-32, 5-33
- isolation (XPI), 4-2
- signal phase, 4-43

Crosspolarized wave, 4-2

CS satellite, 5-3, 5-4, 5-24

CTS satellite, 4-40, 5-4, 5-8

Cumulative statistics, 5-8

- definition, 6-19
- format, 5-5

Cyclonic storm, 2-2

-D-

Data rate reduction, 7-80, 7-120

Debris rainfall, 3-42

Defense Communications Agency (DCA), 7-9

Delay

- ionospheric, 6-5

- tropospheric, 6-5

Department of Commerce (DOC), 6-2

Depolarization

- analysis, 7-58

- data, 4-39, 5-33, 6-105

 - 11.7 GHz

 - 19 GHz, 5-36

 - 28 GHz, 5-36

 - joint depolarization - attenuation, 5-36, 7-60

 - phase variations, 4-43

- definition of terms, 4-1

- hail and snow, 4-6, 6-120

- hydrometeor, 4-4, 6-104

- ice crystal, 4-5, 4-47

 - elevation angle and frequency dependence, 6-113

 - ice crystal parameters, 4-47, 6-115

 - measurements, 6-115

 - model, 4-49, 6-119

- mathematical formulations, 4-7, 6-105

- multipath, 4-4, 6-120

 - due to refractivity gradients

- prediction, 6-104

- rain, 1-6, 4-4, 4-5, 4-23, 6-106

 - CCIR approximation, 1-7, 4-36, 5-33, 6-106

 - elevation angle dependence, 4-45, 6-113

 - experimental results, 4-39, 5-33, 6-107

 - frequency dependence, scaling, 4-45, 6-111

 - phase variations, 4-43, 6-115

 - prediction of statistics, 6-19

 - rate of change, 4-44

 - statistical characteristics, 4-39

 - theory, 4-23

 - versus rain attenuation, 4-33

- snow, 6-120

- sources, 6-104

Design procedure

- examples, 7-44, 7-51, 7-68

- introduction, 7-36

- path performance, 7-37

Distrometer, 2-10

Dispersion, phase and amplitude, 5-39

Diversity

- frequency, 7-79, 7-119

- measures of performance, 7-80

- orbit, 7-79, 7-84, 7-107

- measurements, 7-109
 - path, see site
 - signal 7-111
 - site, 7-79, 7-86
 - definition, 7-80
 - design factors, 7-88
 - empirical models, 7-93, 7-95, 7-102, 7-107
 - experiments, 7-86
 - space, 7-83
- Diversity advantage, 7-81
- Diversity improvement, 7-80
- Diversity gain
 - analytic model, 7-102
 - definition, 7-80
 - empirical model, 7-93
 - empirical model extension, 7-95
 - relative, 7-107
- Drop size distribution, 2-7
- DSCS III satellite, 7-30
- Dust attenuation, 6-73
- Dutton-Dougherty rain attenuation model, 3-2, 3-12

-E-

- ECS satellite, 5-3, 5-4
- Effective path length
 - attenuation model comparisons, 3-70
 - definition, 3-63
 - frequency dependence, 3-64
- Elevation angle scaling
 - depolarization, 6-113
 - rain attenuation, 6-48
- Elliptical polarization, 4-11
- ETS-II satellite, 5-3, 5-4, 5-19, 5-24, 5-35
- European Broadcasting Union, 7-32

-F-

- Fade
 - distribution function, 6-95
 - mitigation, 7-78
 - simultaneous probabilities, 7-121
 - temporal distribution, 5-28
- Fade duration, 5-32, 6-50
 - annual distribution, 5-35, 6-56
 - daily distribution, 6-56
 - versus frequency of occurrence, 6-50
- Federal Communications Commission (FCC), 6-2
- FLTSATCOM satellite, 7-30
- Fluctuations
 - amplitude, 6-76, 6-101
 - antenna aperture effects, 6-75
 - computation of
 - amplitude, 6-101

- angle-of-arrival, 6-103
 - gain reduction, 6-103
 - RMS phase delay, 6-103
- distribution function, 6-95
- example, 6-101
- gain degradation, 6-98
- overview of amplitude, 6-76
- phase, 6-90
- phase delay, 6-90
- phase ripple, 6-92
- phase ripple gain degradation, 6-94
- power spectral density of amplitude, 6-82
- variance of signal amplitude, 6-76

Fog

- attenuation, 6-71
- attenuation prediction model, 6-72
- visibility
- water content, 6-71

Forward error correction (FEC), 7-28, 7-118

- adaptive, 7-79, 7-117

Free space path loss, 7-52

Frequency bands, 6-2

Frequency diversity, 7-79, 7-119

Frequency reuse, 4-1, 5-36

Frequency scaling

- for polarization, 6-111
- for rain attenuation, 5-25, 6-47

-G-

Gain degradation, 6-82

- design information, 6-95
- domains, 6-98
- sample computation, 6-101

Gaseous attenuation

- elevation angle dependence, 6-12
- estimation procedure, 6-12
- frequency dependence, 6-7
- ground station altitude dependence, 6-8
- prediction, 6-6
- sample calculation, 6-16
- sources, 6-6
- standard deviation, 6-9
- surface temperature dependence, 6-12
- water vapor dependence, 6-8

Global rain attenuation model, 1-7, 3-2, 3-17, 6-23

- sample calculation, 6-29

-H-

Hourly Precipitation Data Report, 2-16

Hydrometeors, 4-4

-I-

Ice, meteorological presence, 4-47
Ice depolarization (see: Depolarization, ice crystal)
INTELSAT VI satellite, 7-19, 7-29
Intense rain events
 annual and daily distributions, 6-56
Interference, 6-75
International Radio Consultative Committee: see CCIR
International Telecommunications Union (ITU), 6-2
Ionospheric effects, 6-5
Isolation, 4-4, 4-17
Isotherm, 0°C, 2-4, 3-26, 3-38
ITALSAT satellite, 7-33

-J-

Joss drop size distributions, 2-7

-K-

Laws and Parsons drop size distribution, 2-7
Lin rain attenuation model, 3-2, 3-54
Local Climatological Data Report, 2-17
Low-angle fading, 6-85
 selected experimental results, 6-85
Low-angle scintillation, 6-82

-M-

Marshall-Palmer drop size distribution, 2-7
Model,
 CCIR, rain attenuation, 3-2, 3-44, 6-32
 CCIR, depolarization, 4-36, 5-33
 Dutton-Dougherty, 3-2, 3-12
 Global, 1-7, 3-2, 3-17, 6-23
 ice depolarization, 4-49
 Lin, 3-2, 3-54
 piecewise uniform, 3-59
 rain rate, 3-1
 rain depolarization, 4-23
 Rice-Holmberg, 3-2, 3-5
 SAM (Simple Attenuation Model), 3-2, 3-58
 two-component, 3-2, 3-39
Multipath depolarization, 6-120

-N-

National Climatic Data Center, 2-16
Noise (see also: Sky noise)
 cloud, 6-64
 sky, 1-4, 6-130
 temperature, 1-4
 uplink, 6-143
Non-ideal antenna, 4-15

-O-

OLYMPUS-1 satellite, 7-31, 7-34

- On-board processing, 7-20, 7-25, 7-34
- Orbit diversity, 7-79, 7-84, 7-107
 - measurements, 7-109
- OTS satellite, 5-3, 5-4, 5-18, 5-20
- Outage
 - duration, 7-8
 - period, 3-4
 - time 7-49
- Oxygen absorption, 1-3
- P-
- Partial pressure, saturated, 6-16
- Path diversity (see: Site diversity)
- Performance criteria, 7-7, 7-15
 - analog transmission, 7-12
 - digital transmission, 7-9
 - examples, 7-44, 7-53, 7-68
- Phase dispersion data, 5-39
- Phase fluctuations, 6-90, 6-103, 6-129, 6-131
- Piecewise uniform rain rate model, 3-59
- Polarization isolation, 4-2
- Polarization mismatch factor, 4-10
- Polarization states, 4-7
- Power budget equation, 7-53
- Power control, 7-79, 7-112
 - downlink, 7-115
 - uplink, 7-114
- Power spectral density, 6-82
- Prediction
 - amplitude fluctuations, 6-76
 - angle of arrival, 6-94
 - depolarization, 6-104, 6-122
 - CCIR approximation for rain, 6-106
 - CCIR factor for ice, 6-119
 - fog, 6-72
 - gaseous attenuation, 6-6, 6-11
 - gain degradation, 6-82, 6-103
 - introduction, 6-1
 - phase delay, 6-90
 - power spectral density, 6-82
 - rain attenuation, 6-20
 - CCIR model, 6-32
 - Global model, 6-23
- Propagation beacons
 - ACTS, 7-26
 - Italsat, 7-33
 - Olympus, 7-32
 - summary table, 5-3
- Propagation data, 5-1
 - 11.5 - 11.7 GHz, 5-8
 - 15 - 16 GHz, 5-18
 - 19 - 20 GHz, 5-22

- 28 - 35 GHz, 5-22
- format, 5-5
- phase and amplitude dispersion, 5-39
- satellites used, 5-4
- summaries, 5-1
- temporal fade distribution, 5-28

-R-

Rain

- convective, 2-2
- debris, 3-42
- depolarization (see: Depolarization, rain)
- gauges, 2-23
- gauge integration time, 2-31
- spatial distribution, 2-2
- specific attenuation
- stratiform, 2-2
- volume cell, 3-41

- Rain attenuation, 1-6, 3-1
 - measurements (see: Propagation data)
 - models summary, 3-2
 - model comparisons, 3-61
 - statistics: see Attenuation statistics
 - prediction: see Prediction, rain attenuation

- Rain fade mitigation, 7-78

Rain rate

- climate regions
 - CCIR, 3-45, 6-38
 - Global, 3-21, 6-24
- cumulative distribution, 3-3, 6-26, 6-34
- estimation from rain gauge records, 2-25, 2-28
- long term distributions, 2-3
- measurement, 2-23
- models, 3-2
- path averaged, 3-29, 3-53, 3-55, 3-59
- point, 3-1, 3-15, 3-18
- short term distributions, 2-4
- statistics, 2-1, 3-3
- time variation, 2-25, 3-4, 5-28, 5-32

Rainfall data, sources and types

- Canada, 2-26
- U.S., 2-13
- worldwide, 2-28

- Rate of change of attenuation, 6-56

- Rate reduction, 7-80, 7-112

- Rayleigh scattering, 2-7

- Reflectivity factor, 2-4, 6-122

- Relative humidity, 6-16

- Resource sharing, 7-78

- Rice-Holmberg rain rate model, 3-2, 3-5

-S-